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# A LASER INTERFEROMETRIC MEASUREMENT OF THE TEMPERATURE DISTRIBUTION IN CONVECTIVE THERMAL TRANSFER BOUNDARY LAYERS*

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**ABSTRACT**: By means of a double mirror interferometry a two-dimensional temperature distribution measurement in convective thermal boundary layers is presented. When the cold air flows along a hot plate model, the interferometric fringe inside the boundary layer will bend. According to the displacement of the fringe and the relation between temperature and index of refraction, a two-dimensional temperature profile is obtained. All is accomplished by optical device with the help of micro-computer without any contact with the flow field.

**KEY WORDS**: boundary layer, temperature distribution, laser interferometry

## I. INTRODUCTION

Heat transfer process is important in national defense, energy, chemical and food industries. The determination of physical parameters in the heat transfer process is of great significance for the rational use of energy source, the control of the reaction temperature, the increase of the amount of products and the decrease of the investment.

For the solid plate heat conduction, since the temperature distribution is linear, the amount of heat transfer follows the Fourier law. For convection, since the temperature distribution is non-linear between solid and flow, the amount of heat transfer and the temperature distribution are obtained by solving Navier-Stokes equations. This complicates the problem in the convection process severely.

This problem is simply solved in common practice by means of the film theory. A steady fluid film is assumed existent between solid and flow and the amount of heat transfer from solid to flow or vice versa is solved according to the following equation

$$q=hA\Delta T \tag{1}$$

where $h$ is convection heat transfer film coefficient, $A$ is the area of heat transfer, $\Delta T$ is the temperature difference between solid and fluid. $h$ is a parameter correlated with physical properties and flow characteristics such as $Pr$, $Gr$, $Re$ etc. and can be obtained from experimental results by the similarity rule. It is usually correlated with $Nu$ number. In fact, the fluid temperature and velocity between solid and stream are variable, i. e. the fluid velocity varies from static state along the solid wall to the outside stream-velocity, and the fluid temperature varies from wall temperature to the outside stream temperature. There is no static film existing. Therefore, using static film theory seems somewhat non-realistic.

Once the fluid temperature distribution by the solid wall is known, the structure of the convective thermal boundary layer, the amount of heat transfer and also the approach to improve the convective heat transfer may be examined. The method introduced here for the determination of two-dimensional temperature distribution in a convective thermal boundary layer near the wall of heat plates and heat columns by means of double mirror interferometry is relevant in this respect. The experimental device, the interferometry, the computer treatment,

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typical examples of temperature determination and the comparison with the theory are presented.

## II. EXPERIMENTAL DEVICE

The experiment is carried out in a two-dimensional low speed air tunnel[1]. The exit cross-sectional area is $100 \times 100\,\mathrm{mm}^2$. The hot model is set at the exit. The flow is upward in order to avoid natural convection asymmetry. There are wire gauzes inside the tunnel to rectify the flow. The ratio of cross-sectional area of the rectifying section to the exit is 3 : 1. Air is driven by a blower.

There are two kinds of heat model, namely, plates and cylinders. The dimension of heat plates is $80 \times 100 \times 7\,\mathrm{mm}^3$. In order to observe the effect of different kinds of plate heads on the temperature profile in boundary layers, three kinds of head are used, i.e. the rectangular head, the circular head and a head with 30 degree angle. The length and diameter of the cylinder model are 72 mm and 30 mm respectively. Their axes are set perpendicular to the flow direction to simulate the transverse flow heat transfer in a heat exchanger. The outer walls of these models are made of copper to make the wall temperature uniform. These models may be heated from room temperature to 300 ℃ with heating wires and a transformer. The wall temperature is monitored by a semiconductor thermometer.

Fig.1 is a photograph of the experimental device. A is the air inlet tube, B is the twodimensional air tunnel, C is the beat plate model, D is the double mirror interferometer and E is the laser source consisting of a He-Ne laser and a beam collimator.

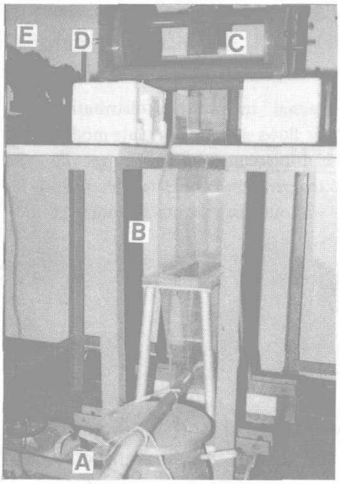

Fig.1 Experimental device
A. Air inlet; B. Air tunnel; C. Heat plate model; D. Double mirror interferometer; E. Laser source

## III. DOUBLE MIRROR INTERFEROMETER

The double mirror interferometer consists of two mirrors and four metal bars. A He-Ne laser is used as the light source. The angle between these mirrors is adjustable to obtain interferograms with different width and different direction of fringes.

The heat model is set between these mirrors. The $80 \times 100\,\mathrm{mm}^2$ plane of plate models and the axis of the cylinder model are set parallel to the light axis to form two-dimensional fields of observation. The horizontal uniform interferometric fringe pattern is shown at the screen of the monitor after adjusting the angle between mirrors at room temperature. When the model is heated, the temperature of air near the model surface is raised due to the convective heat transfer, resulting in changes of the air density and index of refraction, and then a curved interferometic fringe pattern is obtained.

The double mirror interferometer is suitable for measuring the temperature field below 70 ℃ in the boundary layer due to its high sensibility. It is difficult to quantitatively measure the temperature distribution with high temperature degree because interferometric fringes are too close to be distinguished. In this case, a shear interferometer is used after sliding these two mirrors along bars to form a gap. The sensibility of this interferometer is low and may vary with the angle of the air gap. Therefore this interferometer is suitable for measuring high temperature fields[2,3]

## IV. IMAGE PROCESSING[4]

The image processing of the interferogram is as follows:

(1) To find the fringe displacement $\Delta m$ with the help of an A/D unit

The interferogram is taken by a CCD camera and is shown on the monitor of the computer. The two-dimensional gray scale signal is recorded by an A/D unit. The center positions of interferometric fringes are calculated by the computer and a sharp pattern of the interferogram is obtained. The order and displacement of each fringe at each coordinate point $(x, y)$ on the two-dimensional interferogram are then calculated.

(2) To calculate temperature distribution from $\Delta m$

Assuming that the test field is two-dimensional and the index of refraction of air along the light direction is constant, from the difference of optical path equation, we get

$$L\Delta n=(\lambda/2)\Delta m \tag{2}$$

where $L$ is the single path geometrical length of light passing through the test section, $\lambda$ is the laser wave length, namely 6328Å, $\Delta n$ is the difference of the index of refraction between the local high temperature air and the ambient air at room temperature.

The relation between the air index of refraction and the air density $\rho$ obeys the Gladstone-Dale equation:

$$n-1=K\rho \tag{3}$$

where $K$ is the Gladstone-Dale constant. From these two equations and the equation of state, the following relation of the local air temperature with the fringe displacement is obtained.

$$T=T_0+\frac{T_0\Delta m}{(2L/\lambda)(n_0-1)-\Delta m} \tag{4}$$

where $n_0$ is the index of refraction of air at room temperature. The air index of refraction is given by

$$n-1=(n^*-1)\frac{p[1+(1.049-0.0157t)\times 10^{-6}p]}{720.883(1+0.003661t)} \tag{5}$$

where $n_*$ is the index of refraction of air at 15 ℃ and 760 mm Hg, $t$ is the air temperature (℃) and $p$ is the air pressure (mm Hg). For dry air,

$$(n^*-1)\times 10^{-6}=272.7+1.482\lambda^{-2}+0.02\lambda^{-4} \tag{6}$$

where $\lambda$ is the wavelength ($\mu$m).

(3) To draw the chart of temperature distribution

The temperature value at each coordinate point is obtained after the introduction of $(n_0-1)$ and $\Delta m$ into equation (4). By means of a graphic software, a stereograph of temperature distribution on $x$-$y$ plane is drawn. Each curve on this stereograph represents the temperature change of air along $x$ or $y$ directions.

## V. RECTANGULAR HEAD HEAT PLATE PATTERN

Fig. 2 is a photograph of the interferogram taken from the experiment of heat plate model with rectangular head. The black block is the cross-section of the plate. The inclined straight line is the monitor thermometer. When the hot plate is heated, fringes near the wall bend due to the changes of the air temperature and the index of refraction inside the boundary layer. The larger inclination of fringes by the hot wall surface corresponds to higher temperature change. Patterns in both sides are almost symmetrical. The shape and thickness of the boundary layer can be seen along the intersection of curved and flat fringes in the interferogram.

Fig.3 shows the sharp pattern of the interferogram on the right part of Fig.2. The numbers of coordinate points in this figure are 272 × 30. Fig.4 shows the stereograph of the two-dimension temperature distribution drawn from values calculated at each coordinate point. It is shown that the air temperature by the wall is almost equal to the surface temperature of the hot plate, and that far from the hot plate is equal to room temperature. The air temperature on the left side is higher than that on the right side due to the cooling effect of the natural convection.

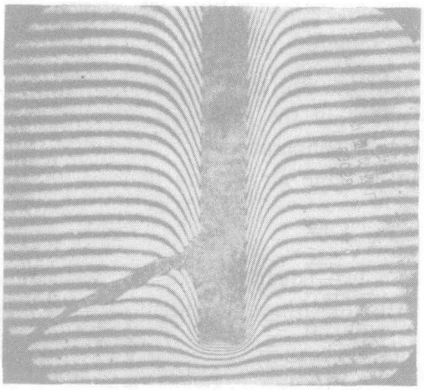

Fig.2 The interferometric photograph of boundary layer

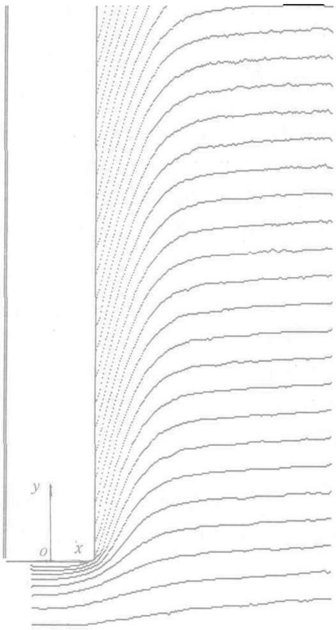

Fig.3 Center lines of interferometric fringes

## VI. THE TEMPERATURE DISTRIBUTION FOR OTHER MODELS

Table 1 gives experimental conditions for models of plates and cylinders. Interferograms of these experiments are similar, namely, curved near the hot surface and flat outside the flow. The shape and dimension of the thermal boundary layer may be estimated from the edge of

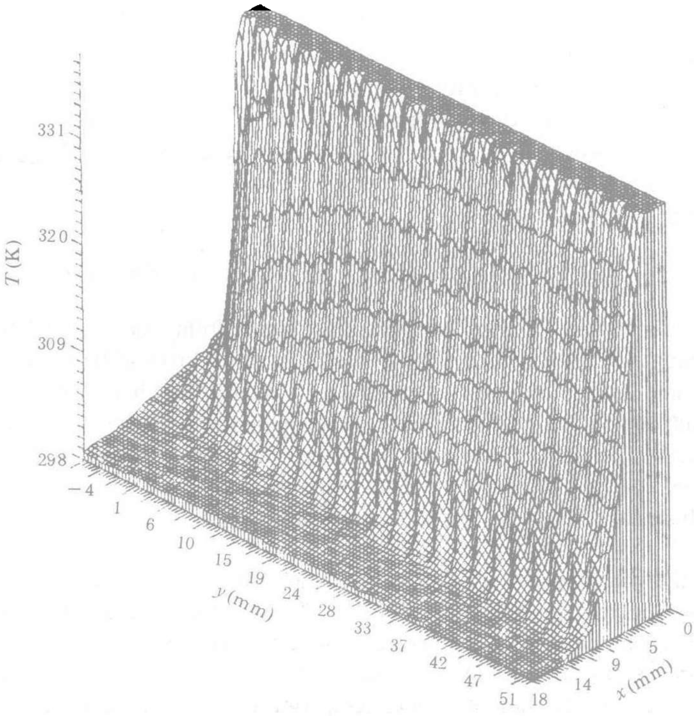

Fig.4 Temperature distribution in boundary layer

the curved part. It can also be seen that, the width of boundary layers with forced convection is narrower than that with natural convection. The temperature distribution of these experiments is also similar to that shown in Fig.4.

**Table 1** Experimental conditions

| run No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Model type | plate rectangular head | plate circular head | plate rectangular head | plate circular head | plate rectangular head | plate angular head | cylinder | cylinder |
| Monitor temperature (℃) | 60 | 21 | 15 | 21 | 20 | 17 | 30 | 30 |
| Room temperature (℃) | 25 | 16.9 | 11.4 | 16.9 | 11.4 | 11.4 | 16.9 | 16.9 |
| Air velocity (m/s) | natural convection | natural convection | natural convection | 0.5 | natural convection | natural convection | natural convection | 0.5 |

## VII. DISCUSSION

On stereogaphs obtaind from this study, there are constant temperature planes and high temperature regions far from and near the hot surface, respectively. This obviously conforms to the physical phenomenon.

The blur of the interferometric fringe at the surface of the hot plate is due to the diffraction of the laser beam. In fact, the temperature peak on the stereograph is only the air temperature at $x \approx +3.56$ mm. The air temperature just at the hot plate surface $x = +3.50$ mm may be extrapolated from this temperature peak and the temperature gradient at this point. Table 2 shows the air temperature just at the hot plate surface for four different runs and the corresponding monitor temperature. It is seen that these values coincide with each other for every run.

**Table 2** Air temperature at hot plate surface (K)

| run No. | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Fringe No. | | | | |
| 4 | 294.8 | 286.5 | 294.52 | 291.69 |
| 5 | 294.85 | 286.3 | 294.30 | 292.38 |
| 6 | 294.91 | 286.47 | 294.50 | 292.35 |
| 7 | 294.95 | 286.58 | 294.49 | 294.34 |
| 8 | 295.24 | 286.56 | 294.44 | 292.44 |
| 9 | 294.84 | 286.74 | 294.58 | 293.04 |
| Monitor temperature (K) | 294 | 288 | 294 | 293 |

From Table 2, it is also seen that different experimental conditions give different temperature measurement values. The temperature values of run No.2 and 4 are almost the same due to the same experimental condition, except that, the air temperature at the hot plate surface of run 4, which is for forced convection with higher heat transfer rate, is a little bit less than that of run 2 for natural convection. This difference is also shown in other corresponding stereographs. Therefore, by means of the method presented in this paper, the temperature change caused by different flow condition is also distinguishable.

According to reference [5], the $Nu$ number of natural convection heat transfer perpendicular to a half infinite flat plate with constant temperature is

$$Nu_1=\frac{3}{4}\left[\frac{2Pr}{5(1+2Pr^{1/2}+2Pr)}\right]^{1/4}[Gr\cdot Pr]^{1/4} \tag{7}$$

where $Gr$ and $Pr$ are dimensionless numbers.

The temperature gradient close to the hot plate surface measured by the present method gives

$$Nu_2=-\left(\frac{dT}{dy}\right)_w\frac{y}{T_w-T_0} \tag{8}$$

where $y$ is the distance from the edge of the hot plate and $T_w$ is the wall temperature of the plate calculated as the air temperature at the point of consideration.

By comparing these two $Nu$ numbers at the same point the degree of agreement for the measured temperature with references may be estimated. Table 3 shows the comparison of run No.3, in which values of $Nu_1$ and $Nu_2$ at each point are close to each other. For other interferograms, $Nu_1$ is two to three times more than $Nu_2$ due to the difficulty of the determination of temperature gradients.

**Table 3** Comparasion of $Nu$ number (run No.3)

| Fringe No. | $y$ (mm) | $\left(\frac{dT}{dy}\right)_w$ | $Nu_2$ | $Nu_1$ |
|---|---|---|---|---|
| 4 | 4.9 | 1.958 | 4.6 | 5.0 |
| 5 | 8.8 | 1.495 | 6.2 | 7.6 |
| 6 | 12.6 | 1.659 | 10.2 | 10.2 |
| 7 | 16.7 | 1.659 | 12.7 | 12.7 |
| 8 | 20.8 | 1.659 | 15.9 | 14.9 |
| 9 | 24.6 | 1.21 | 14.1 | 16.8 |

The above temperature values are calculated directly from Eq.(4) by using $T_0$ and $\Delta m$ at each coordinate point without any identification in advance.

The error of the present method comes from the following factors:

(1) System error —— The twisted error of fringes on the interferogram using double plane mirror is $\lambda/10$[6].

(2) Reading error —— The reading and smoothing treatment of the computer introduces error less than $\lambda/20$.

(3) Diffraction error —— The diffraction error due to the boundary effect is 6%[6].

(4) Condition error —— This is due to the neglect of the change of the index of refraction in the air flow near the edge of the hot plate. By estimation[7], this kind of errors for run No.1 to 5 are 7.8%, 6.7%, 8.3%, 2.3% and 7.3% of the temperature rise respectively. This error may be reduced by lengthening the test section.

## VIII. CONCLUSION

1. By means of a double mirror interferometry, the two-dimensional temperature distribution in a convection thermal boundary layer may be determined with the method described in this paper. All is accomplished by the optical method with the help of a micro-computer.
2. On stereographs obtained from this study, there are constant temperature planes and high temperature regions far from and near the hot surface respectively. This conforms to the physical phenomenon.
3. By comparing the monitor temperature and the $Nu$ number as discussed, the temperature distribution measured by this method is reliable.

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